REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	23 September 1993	Final Report

4. TITLE AND SUBTITLE

On the Non Linear Spanwise Interaction of Disturbancews Emanating from Two Point Sources in a Blasius Boundary Layer

5. FUNDING NUMBERS

F6170892W0385

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8. PERFORMING ORGANIZATION REPORT NUMBER

SPC-92-4010

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC-92-4010

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Localized disturbances in a laminar boundary layer simulate transition more realistically than the extensively studied, two-dimensional perturbations regardless of the fact if they evolve in a linear manner or not. Localized disturbances can originate by surface imperfections, insects, or dust. The disturbances can be harmonic (i.e. containing a single frequency and a band of spanwise wave numbers) or pulsed (i.e. containing a band of both streamwise and spanwise wave numbers). At sufficiently low amplitudes, localized disturbances evolve in accordance with the linear stability theory and the assumption of parallel flow presents no difficulty. It is highly probable that in naturally transitioning boundary layers such localized disturbances will overlap and interact. These interactions could either delay transition because of a partial wave cancellation resulting in disturbance attenuation, or enhance transition by promoting non linear interactions. The non linearity could arise from the finite amplitude of the perturbation or may be caused by a resonant wave triad. Non linear processes in a wave packet lead to breakdown and to the formation of turbulent spots. When the amplitude of the localized harmonic disturbance saturates, the non linear processes widen the band of the amplified lower frequencies adjacent to the excitation frequency. Experimental results describing the spanwise interaction of two harmonic or two pulsed localized disturbances leading to breakdown are presented and discussed. A comparison to the evolution and breakdown of single localized disturbance is provided. It was observed that spanwise interaction of localized disturbances promotes transition. The interaction between disturbances emanating from two harmonic point sources results in a rapid broadening of the spectral peak surrounding the excitation frequency while the interaction of two wave packets generates two new bands of frequencies at half and twice the dominant frequency of the wave packet. These new spectral peaks become broad and "fill" the rest of the spectrum.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
	32	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

On the NON LINEAR SPANWISE INTERACTION of DISTURBANCES EMANATING from TWO POINT SOURCES in a BLASIUS BOUNDARY LAYER

FINAL REPORT SUBMITTED TO EOARD AFOSR
(contract number F61708920385)

by

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ABSTRACT

Localized disturbances in a laminar boundary layer simulate transition more realistically than the extensively studied, two-dimensional perturbations regardless of the fact if they evolve in a linear manner or not. Localized disturbances can originate by surface imperfections, insects or dust. The disturbances can be harmonic (i.e. containing a single frequency and a band of spanwise wave numbers) or pulsed (i.e. containing a band of both streamwise and spanwise wave numbers).

At sufficiently low amplitudes, localized disturbances evolve in accordance with the linear stability theory and the assumption of parallel flow presents no difficulty. It is highly probable that in naturally transitioning boundary layers such localized disturbances will overlap and interact. These interactions could either delay transition because of a partial wave cancellation resulting in disturbance attenuation, or enhance transition by promoting non linear interactions. The non linearity could arise from the finite amplitude of the perturbation or may be caused by a resonant wave triad. Non linear processes in a wave packet lead to breakdown and to the formation of turbulent spots. When the amplitude of the localized harmonic disturbance saturates, the non linear processes widen the band of the amplified lower frequencies adjacent to the excitation frequency.

Experimental results describing the spanwise interaction of two harmonic or two pulsed localized disturbances leading to breakdown are presented and discussed. A comparison to the evolution and breakdown of a single localized disturbance is provided. It was observed that spanwise interaction of localized disturbances promotes transition. The interaction between disturbances emanating from two harmonic point sources results in a rapid broadening of the spectral peak surrounding the excitation frequency while the interaction of two wave packets generates two new bands of frequencies at half and twice the dominant frequency of the wave packet. These new spectral peaks become broad and "fill" the rest of the spectrum.

INTRODUCTION

Velocity perturbations occurring naturally in a boundary layer are seldom harmonic or two dimensional. They often originate at surface imperfections and are precipitated by temporally random disturbances in the free stream. Moreover, it is highly probable that two or more such localized disturbances will overlap and interact. Such an interaction might promote transition to turbulence. Nevertheless, the most detailed information available about the growth or decay of disturbances in boundary layers focuses on a somewhat artificial case of a harmonic motion in two dimensions. The current understanding of the possible means of controlling such disturbances is even more restricted. Tollmien-Schlichting waves of identical frequency, emanating from two, 2D harmonic sources displaced in the direction of streaming, may either reinforce or weaken one another depending on the phase relationship between them. The possibility of wave cancellation is attractive because it may be used to delay the transition from laminar to turbulent flow. Two dimensional wave interactions were first investigated by Wehrmann (Ref. 3), by Liepmann et. al (Ref. 4), Thomas (Ref. 5) and most recently by Popator and Saric (Ref. 6). A single mode of oblique waves could also be controlled in a similar manner, but the suppression of complex 3D disturbances originating randomly by a variety of sources represents a task of a different magnitude.

Isolated disturbances emanating from a single point source were studied by Gaster (References 7 and 8) and Mack (Ref. 2), following some pioneering work of Benjamin (Ref. 9) and of Criminale and Kovasznay (Ref. 10). The disturbances investigated are either continuous or time dependent and consequently they were generated by either a harmonic point-source or by a pulse. Gaster (Ref. 7) showed that three dimensional wave-packets, constituting of a finite band of frequencies and spanwise wave numbers propagating in a boundary layer, can be generated by a localized impulsive disturbance (e.g. a brief and tiny vertical jet). Such a disturbance produces a flat, broad-band spectrum which is selectively amplified by the boundary layer to contain a dominant band of 2D and 3D wave numbers. Gaster's theoretical model (Ref. 7) was based on the integration of Eigen modes calculated from the Orr-Sommerfeld equation making use of Squire's theorem (Ref. 11). These calculations resembled the observed, initial development of the wave-packet at the outer edge of the boundary layer (Ref. 8).

Mack and Kendall (Ref. 2), and Kachanov (Ref. 1) investigated the evolution of a wave train produced by a harmonic-point-source (HPS) in a Blasius boundary layer. Mack's calculations indicated that the maximum amplitude of the disturbance lies on the ray emanating from the source and defined by $Zs / Xs = 0.05$ to 0.09 (where Zs and Xs are the

spanwise and streamwise distances measured from the source of the disturbance and his calculations were carried out for a reduced frequency F=60 at typical Reynolds numbers R = 800 to 1000), rather than on the plane of symmetry as expected from the simplified interpretation of Squire's theorem. These calculations are in good agreement with experimental observations (References 1 and 2).

The non linear, spanwise interaction between two harmonic disturbances or two wave packets emanating from spatially separated point-sources located in a fully developed Blasius boundary layer is considered presently. The two spanwise HPS interaction is much simpler interaction than the one occurring between wave packets yet it contains some important three dimensional and non linear ingredients which need to be clarified before proceeding to a more complicated even though more realistic interaction between wave packets. The simpler kind of interaction enables us to study separately the effects of three dimensionally and finite amplitude of the imposed harmonic oscillations in comparison to the interaction among many waves which are all present simultaneously in wave packets.

In the previous stage of the experiment (Ref. 16) special attention was paid to those linear, three-dimensional interactions which might precipitate large amplitudes even when the amplitudes of the individual, non interacting perturbations are small.

The project was subdivided into three parts consisting of:

(i) a detailed investigation of a single harmonic disturbance originating from a point;

(ii) an interaction of two harmonic disturbances displaced in the spanwise direction,

(iii) a numerical simulation of a linear interaction between two harmonic disturbances displaced in the direction of streaming.

We concluded then that the evolution of an isolated, harmonic point-source disturbance, in a boundary layer is well predicted by a linear model. Furthermore, the spatial interaction of two or more such low amplitude disturbances, can be modeled by linear superposition in spite of the complicated phase relationships among such disturbances. This simplification enables one to predict the net effect of any desired distribution of point source disturbances, as long as the resulting amplitudes are still low. It was also concluded that the total suppression of a harmonic, point-source disturbance within a short streamwise distance is virtually impossible to achieve unless one contemplates a distributed control mechanism consisting of a large number of individually controlled actuators. This conclusion should also be valid for the impulsively generated three dimensional wave-packet because its spanwise structure consists of Fourier components, which are individually identical to the harmonic-point-source disturbance (Ref. 14).

The evolution of a wave packet in a Blasius boundary layer was investigated experimentally by Cohen et. al (Ref. 15). They followed the wave packet from it's initial low amplitude stage through the weakly non linear stage until it developed into a turbulent spot. They concluded that the non linearity is marked by a resonant sub harmonic wave triad as suggested by Craig (Ref. 17). The manner in which the harmonic point source disturbance departs from its linear behavior was not investigated to the best of our knowledge and it will be described in this report. The report will also focus on the non linear interaction between two harmonic point sources as well as on the interaction between two wave packets. The primary objective of this study is to determine the role of such interaction in promoting boundary layer transition.

THE EXPERIMENT

The spatial evolution of a single wave train or a single wave packet and the interaction between two wave trains or two wave packets emanating from separate point sources, located in a Blasius boundary layer and displaced in the spanwise direction, were investigated experimentally. The experiment was conducted in the close loop, low turbulence wind tunnel (the rms level of the u' fluctuations at U=8m/s was less than 0.03% with the plate, its flap and the traversing mechanism being installed in the tunnel) at Tel-Aviv university. The entire experiment was computer controlled. The automation encompassed hot-wire calibration procedure and probe traversing even in the proximity of the wall. A polished aluminum plate 19 mm thick and 2.5 m long was installed vertically in the 3.0 m long test section. The plate has an elliptic leading edge and an adjustable trailing-edge flap which controls the circulation around the plate thus altering the location of the leading-edge stagnation line. The turbulent corner flows originating at the juncture of the plate and the tunnel walls were forced to bleed to the backward side of the plate through adjustable slots. This was achieved by a slight increase in the static pressure on the working side of the plate and it helped to maintain a long fetch of laminar flow on that surface. The free stream velocity was maintained at 7.5 m/s throughout. The calculated Reynolds number based on the measured displacement thickness agreed with the expected values for the Blasius boundary layer. The spanwise distribution of R in the region of interest was maintained at its nominal value within ±2.5%. The top and bottom walls of the test section were adjusted until the measured Falkner-Skan Parameter (FSP) vanished, or at least did not exceed the value ±0.05, which was within the possible resolution of the measurement. The FSP is a very important parameter strongly affecting the critical Reynolds number and the linear amplification factor. The controlled harmonic disturbances (generating a wave train) or the pulsed jet (resulting in a wave packet) were generated by two miniature earphones (used commercially for hearing-aids) embedded in the rear side of the flat plate and ejecting small vertical jets of air through 0.5 mm holes. These sources were located 30 or 50 cm from the leading edge of the plate, corresponding to R=700. The spanwise separation between the two point sources was 80 or 120 mm which was equivalent to 50-80 local displacement thicknesses at the free stream velocity of 7.5 m/s and also amounted to two or three wave lengths of a typical perturbation at the dimensionless frequency of F=104. Both earphones were activated by the same input signal and their output strength was matched in order to produce equal amplitude harmonic waves at any desired phase shift. The disturbances originating from a single harmonic-point-source spread in the spanwise direction at half an included angle of 8-10°,

consequently the prescribed spanwise separation between the sources allowed each wave train to develop independently before it overlapped and interacted with its neighbor.

A schematic representation of the experiment is sketched in Figure 1. The experimental assessment of the spanwise interaction was done in three steps. In the first step both sources operated simultaneously while subsequently each source operated alone under identical flow conditions. In this way, any residual asymmetry in the flow or any uncontrollable perturbation in the tunnel would affect all three stages of the experiment equally and could be subtracted out. The amplitude and phase distributions of the stream wise component of the velocity fluctuation were calculated from data sampled across the entire boundary layer at every X,Z location. More than 30 points of the streamwise velocity component were measured within the boundary layer between the wall and the Y location corresponding to 4 displacement thicknesses. The maximum amplitudes presented were determined with respect to Y at every X,Z location while the phase reference was chosen at the location at which the amplitude was maximum (i.e. Yma). The flow was interrogated along the center-plane of every isolated harmonic disturbance (i.e. Z=Zp) and along the plane of symmetry of the combined disturbance (i.e. at Z=0).

Traverses across the entire span of the disturbance were made only at a few select streamwise locations. However, in this report we focused on the non linear manifestations which are clearly amplitude dependent. Most of the data presented is for the Y location corresponding to the maximum amplitude (were the local mean velocity is approximately 35% the free stream velocity).

DISCUSSION OF RESULTS

Initial Evolution of the Localized Disturbances

As reported previously (Ref. 16) the disturbances were introduced in a manner which assured that their initial evolution was linear (i.e. it agreed with linear theory). The following observations support the above statement:

a) The HPS amplitude and phase distributions match the values predicted by linear theory;

b) The perturbation resulting from the interaction of two HPS evolves intially linearly [i.e. as long as the streamwise distance from the source of the disturbance (X-Xp) is less than 1m and for maximum amplitudes lower than 0.4%];

c) The amplitude and phase distributions within a wave packet (WP) agree very well with the HPS data (for the same frequency parameter) ;

d) The two WP interaction is equivalent to a linear superposition of two separate wave packets.

The Evolution of a Disturbance Emanating from an Isolated HPS

We introduced harmonic oscillations to the flow at a single point and as long as these perturbations had sufficiently low amplitudes so as to evolve linearly, the data was reduced and averaged relative to the phase of the disturbance. It is questionable whether this technique can be used also when the waves evolve in a non linear fashion. In order to clarify this issue we examined the amplitude and phase of the fundamental excitation frequency at many locations across the boundary layer directly downstream of the Harmonic Point Source . It was found that, up to a certain streamwise location, the phase distribution resembles the linear model prediction (Fig. 2), but beyond it the phase distribution, even at the excitation, frequency is incoherent and appears to jitter inside the boundary layer. When such a signal is phase locked to the disturbance, the ensemble averaged data is also scrambled in phase. From this point on, the full spectrum of the velocity perturbation should be considered. The evolution of an isolated HPS - disturbance at a dimensionless frequency of F=104 is presented in figure 3 for two spanwise locations: directly downstream of the HPS (i.e. along the centerline of the evolving disturbance Z=Zp=-4cm) and another along Z=0 (which would be the line of symmetry along which the interaction takes place).

Up to a distance of X=1000mm. from the leading edge, (the source of the disturbance is located at Xp=500mm in this case) the maximum amplitude can be reasonably predicted by the linear model. Please note that the amplitude at Z=0 is greater than on Z=Zp at 750<X<1000mm. which indicates that the most unstable mode in this region is a 3D mode. At X>1000mm the excited wave (i.e. the fundamental frequency) becomes saturated. The phase locked amplitudes of the sub harmonic (F/2) as well as the first harmonic (2F) frequencies are very low at X<1200mm. Between X=1100 and 1200mm the phase of the fundamental frequency is randomized (Fig. 2) due to non linear effects. At X>1200mm the amplitudes of F/2 and 2F are increased rapidly. At X=1500mm the amplitude of F/2 exceeds that of F. From X=1300mm and downstream the intermittency factor (i.e. the time fraction in which the signal is turbulent) increases also very rapidly (figure 3). From these observations it appears that the non linear activity originates at Z=Zp for the isolated HPS but it spreads to Z=0 within 100mm. further downstream.
Another and probably more comprehensive observation can be made by examining the complete spectrum of the disturbance generated by the HPS at Z=0 and Yma. (i.e. the Y location at which the disturbance attains its maximum amplitude). At X>100cm. the fundamental saturates and the adjacent frequencies lower than F are amplified between X=100 and 120cm. (figure 4). Between X=120 and 140cm the amplitude of the fundamental remains unchanged while the amplitudes in the frequency band surrounding the fundamental frequency increase significantly. Further downstream (X=160cm) an almost complete "filling up" of the frequency spectrum is observed.
The effect of changing the amplitude of the fundamental forcing frequency is presented in figure 5, where a comparison is made between the evolution of two harmonic disturbances differing only in their initial amplitudes. Similar effects were observed at both amplitudes of excitation except that the streamwise locations where these effects were observed depended on the initial amplitude. The amplitude of the fundamental wave (F) in the case of the low amplitude excitation increases again at X>1300mm. due to non linear interaction (figure 5a). The amplification rates of F/2 wave and of the 2F wave (as assessed from the slope of these amplitudes versus X) are also lower for the lower forcing amplitude.

The non linear, streamwise evolution of an isolated HPS can be subdivided into a few distinct stages:

a) Saturation of the fundamental frequency;
b) Amplification of frequencies surrounding the fundamental frequency by some kind of a frequency detuning mechanism;

c) Randomization of the phase which is accompanied with the "filling-up" of the spectrum;

d) Detection of intermittent turbulence.

The Spanwise Interaction of Two HPS disturbances

Spanwise interaction between two identical harmonic point-source disturbances, emanating from the same X coordinate but from different Z locations, was studied in the second stage of the experiment. The disturbances originated at Xp=500mm and Zp=± 40mm. This spanwise separation accounts for approximately two wave lengths of the excitation frequency F=104 (60Hz at 7.5m/s in air at 25°C).

The local, phase locked maximum amplitudes, measured for the two levels of initial excitation are presented in figure 6 along Z=0 (the plane of symmetry of the interaction). At the lower excitation amplitude, the evolution of the primary wave appears to be linear (at least up to Xs=900mm), based on the constancy and the low amplitude of the F/2 and 2F waves. The fundamental wave generated at higher excitation amplitude saturates at Xs=500 (i.e. at X=1000mm). Around Xs=600mm the two waves generated by the non linear interactions (i.e. the F/2 and 2F frequencies) begin to amplify. The phase of the forcing frequency becomes random across the boundary layer between Xs=800 and 900mm. (figure 7) and from that point downstream, the amplitude of the fundamental decays somewhat (possibly in part due to the phase jitter). At Xs>900mm turbulence appears and its intermittency factor increases with increasing downstream distance (i.e. the fraction of time at which the flow is turbulent increases with X; see figure 6b). At Xs=1000 mm the amplitude of F/2 exceeds that of F. At Xs>1100mm the amplitudes of F/2 and 2F saturate as well, indicating perhaps that a new equilibrium situation has been attained. Examining the amplitude spectra for the two HPS interactions on the plane of symmetry Z=0 (figure 8) indicates that there is a rapid widening of the amplified frequency band around the fundamental at 1000<X<1200 mm. where the amplitude of the fundamental remains saturated. Between X=1200 mm. and 1300 mm. the spectral broadening occurs mostly on the high frequency side of the fundamental. At X>140cm the spectrum resembles that of a turbulent flow. Comparing the spectra associated with the single HPS (figure 4) to the spectra generated by the interacting 2-HPS disturbances on Z=0 (figure 8) reveals that the process of "filling-up" the spectrum is accelerated by the interaction. Turbulent state sets in at lower X distances due to the interaction. Clearly the 2-HPS interactions promote transition. However, there was no evident difference in the observed non linear mechanism leading to transition to turbulence in the isolated and the interacting harmonic disturbances.

The Non Linear ,Two Wave-Packet Interaction.

The evolution of a low amplitude isolated wave packet to a turbulent spot was documented elsewhere (Ref. 15). We shall thus concentrate on the non linear aspects of spanwise interaction between two wave packets. The streamwise evolution of an isolated wave packet was determined for the sake of completeness, and an example of this data is shown in figure 9. The maximum amplitude of the velocity perturbation was only 0.1% and it was established from the slope of the envelope which was fitted to the data at distances varrying from 35 to 55cm downstream of the point at which the perturbation was generated. The signals plotted in figure 9 represent a few hundred events which were ensemble averaged. Raw velocity signals resulting from two interacting wave packets are plotted in figure 10. These signals were measured 170cms downstream of the points of generation on the plane of symmetry of this interaction which happens to be at Z=2cm. relative to our fixed coordinate system. The bottom velocity signal represents an event which was weakly amplified and resembles the ensemble averaged signals presented in figure 9. The middle signal in Figure 10 has a larger amplitude but it is still in a laminar state. The upper trace in figure 10 represents a highly amplified event on the verge of becoming turbulent. It is also evident that the leading interface of the high amplitude perturbation arrived earlier at the measuring location. It is well known that strong disturbances propagate faster than low amplitude disturbances in a laminar boundary layer (e.g. the average celerity of a turbulent spot is 65% of the free stream velocity while the phase velocity of TS-waves is approximately 35% the free stream velocity).

An isometric view of the velocity perturbation in the Z-t plane resulting from the passage of the two interacting wave packets is plotted in figure 11. The centerline of each individual wave packet is located at Z=4 and -4cm while the plane of symmetry of the interaction is at Z=0 for this case. The two wave packets originated at the same time from the same streamwise location and their amplitudes were very carefully matched. The highest amplitude was measured at Z=0 where the most probable non linear evolution resulting from the interaction of the two wave packets occurs.

One of the characteristic features of the non linear interaction is the appearance of new peaks in the power spectra. In the present case we measured the amplitude spectrum of each isolated wave packet and repeated the procedure for the interacting two wave packets. The three power-spectra are presented in figure 12. In this experiment the two wave packets originated at Xp=30cm and were separated 12 cms in the spanwise direction. The band of amplified frequencies for the individual wave packets lies between

30 and 70Hz with a dominant frequency of 47Hz. The amplitudes of the two individual wave packets are almost identical, while the amplitude of the interacting two-wave packets is approximately equal to the sum of the two isolated wave packets in the central band of the unstable frequencies. The non linearity stemming of the interaction of the two wave packets is manifested by the two new bands of amplified frequencies which are not apparent in the absence of the spanwise interaction. Theses bands are centered around 20 and 90Hz, or about half and twice the dominant frequency of the isolated wave packet.

Another important feature affecting the non linearity of the 2-WP interaction is the relationship between the streamwise and spanwise wave numbers participating in the interaction. The Streamwise wave number can be controlled by altering the streamwise location at which the wave packet is introduced (the most amplified wave numbers scale with the local boundary layer thickness and are also affected by the stability characteristics of the laminar boundary layer which selectively amplifies shorter waves, of higher F, at lower Reynolds numbers), while the spanwise wave number can be controlled by altering the spanwise separation between the two sources. Indeed , the non linearity is very sensitive to the wave number ratio taking part in the interaction. In order to quantify the non linearity of the interaction we defined a "non linear term" as the difference between the amplitude spectrum measured during the passage of the interacting two wave packets and the linear superposition (sum) of the two spectra measured during the passage of each isolated wave packet. This non linear term is plotted in Figure 13b (lower part) for three combinations of spatial locations. The amplitude spectra of these two interacting wave packets are plotted in figure 13a. When the two sources were located at Xp=50cm and Zp=±4cm very little non linear activity was observed. However, when the spanwise separation was increased from 8cm to 12 cms, strong non linear activity was observed at and around 20 and 90 Hz. When the ratio between the spanwise and streamwise wave lengths was further increased by moving the sources to Xp=30cm (reducing the streamwise wave length while keeping the spanwise separation at 12cms, strong non linear activity was observed around 25, 55 and 85Hz. These findings suggests that the non linear mechanism governing the interaction of the two wave packets is a triad resonance, sensitive to the specific wave numbers present.

After finding that the interaction promotes non linear activity we shall try to answer the question: Does the spanwise interaction promote transition? or would the result be identical to the evolution of a single wave packet having an original amplitude equivalent to the sum of the input disturbances at the two spanwise locations?

A comparison between the amplitude spectra of the 2-WP and the spectra of the two isolated WP is presented in figure 14a. At the location shown, the amplitudes of the two individual wave-packets are not identical, nevertheless the amplitude of the interacting 2-WP has 3 distinct peaks at frequencies of 17, 30 and 70 Hz which were amplified due to the interaction. A comparison between the spectrum observed for the isolated wave packets generated by two different levels of disturbance and the spectrum observed due to a 2-WP interaction is made in figure 14b. The high amplitude single WP has a dominant peak in the spectrum at the same amplitude as does the 2-WP interaction. The non linearity observed during the 2-WP interaction is clear around 30, 70 and 90 Hz.

It can be concluded that spanwise interaction of 2-WP also promotes transition, in comparison to a high amplitude, isolated WP instability. This non linearity is associated with the generation of dominant peaks in the spectrum around the harmonic and the sub harmonic of the linearly most amplified disturbances. This process is very sensitive to the dominant ratio between the streamwise and spanwise wave numbers of the interacting perturbations.

CONCLUSIONS

Spanwise interaction of localized disturbances of short duration (characterized intially by wave-pakets) promote transition not only by increasing the amplitude of the disturbance in the interaction zone but also by generating broad spectral peaks around the harmonic and the sub harmonic frequencies. It is believed that the generation of the sub harmonic stems from a triad resonance. This kind of interaction is very sensitive to the ratio between the spanwise and streamwise wave numbers.

Transition may also be caused by an Isolated Harmonic Point Source Disturbance as well as by Interacting Two Harmonic Point Sources. In these cases one observes a gradual amplification of waves adjacent to but lower than fundamental forcing frequency. This contributes to the detuning of the fundamental excitation frequency. Phase scrambling of the perturbation across the boundary layer is also noticeable in this case.

These findings support the assumption that spanwise interaction of naturally occurring localized disturbances in a laminar boundary layer is a possible and probable route to transition.

ACKNOWLEDGMENTS

The assistance of Mr. Barak Margaliot and Mr. Yosef Mytnik in gathering and processing the data is appreciated.

This project was supported in part by a contract from the United States Air Force (EOARD AFOSR) and monitored by Dr. W. Calerese.

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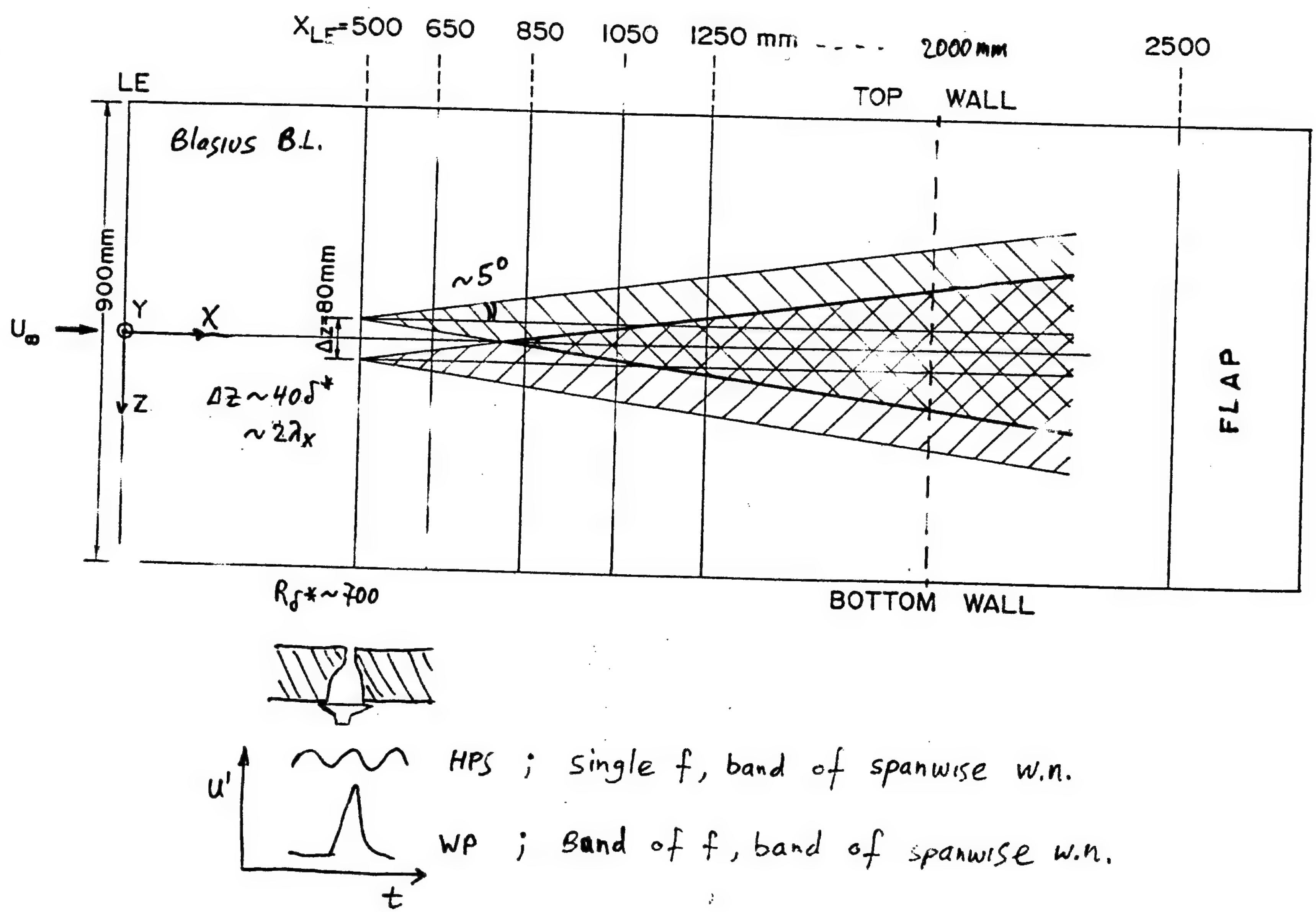
FIGURE CAPTIONS

Fig. 1	Flat plate arrangement and disturbance generator.
Fig 2	Phase randomization alters the shape of the phase distribution due to non-linearity.
Fig. 3	Phase locked Max amplitude of F, F/2 and 2F and Intermittency factor of a Single HPS evolution on Z=Zp and Z=0. F=104e-6.
Fig. 4	Amplitude spectra of a Single HPS on Z=0 at Y of 35% free stream velocity (Yma) at various X locations. F=104.
Fig. 5	Phase locked Max amplitude of F, F/2 and 2F of a Single HPS evolution on Z=Zp and F=104e-6 for two excitation amplitudes.
Fig. 6	Phase locked Max amplitude of F, F/2, 2F and Intermittency factor for THPS Interaction (Z=0).
Fig 7	Phase randomization alters the shape of a Single HPS (Z=Zp) and THPS Interaction (Z=0) phase distribution due to non-linearity.
Fig. 8	Amplitude spectra of a THPS Interaction on Z=0 at Y of 35% free stream velocity (Yma) at various X locations. F=104.
Fig. 9	Velocity perturbation due to WP passage at Xs=35 to 55 cm. WP envelope and interfaces (propagation velocities indicated) also presented.
Fig. 10	Individual realizations of TWP interaction.
Fig. 11	Plan view of the velocity perturbation due to TWP Interaction passage at Xs=55 cm. Yma.
Fig 12	Amplitude spectra of a TWP Interaction on Z=2cm (Zp=-4 and 8cm) at Yma compared with the spectra of two isolated WP at the same location.
Fig 13	Amplitude spectra of a TWP Interaction for three relations between streamwise and spanwise wave numbers (upper part) along with the non linear term (lower part).
Fig 14	Amplitude spectra of single WP at different amplitudes and TWP Interaction.



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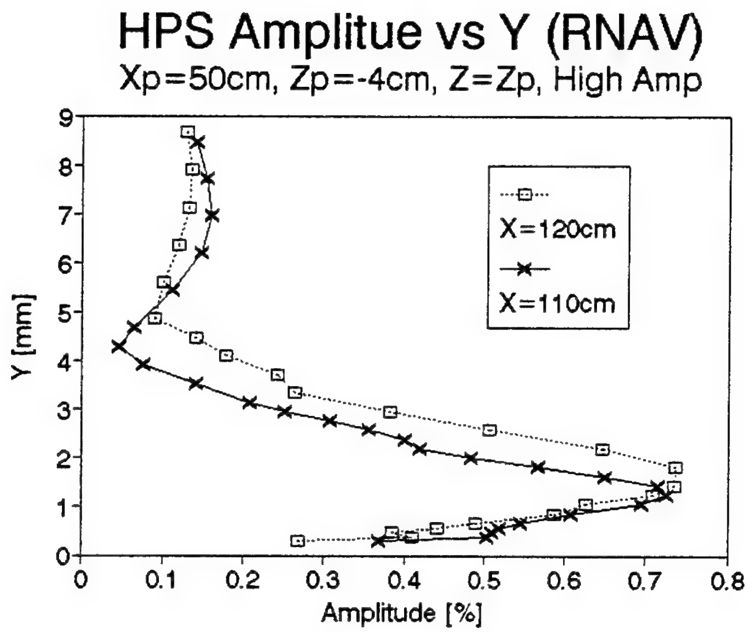
X
Z
Δz=80mm
~5°
Δz ~ 40δ*
~ 2λx
FLAP
Rδ* ~ 700
BOTTOM WALL
u'
t
HPS ; single f, band of spanwise w.n.
WP ; Band of f, band of spanwise w.n.

fig. 1


HPS Amplitue vs Y (RNAV)
Xp=50cm, Zp=-4cm, Z=Zp, High Amp
X=120cm
X=110cm
Y [mm]
Amplitude [%]
0
1
2
3
4
5
6
7
8
9
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

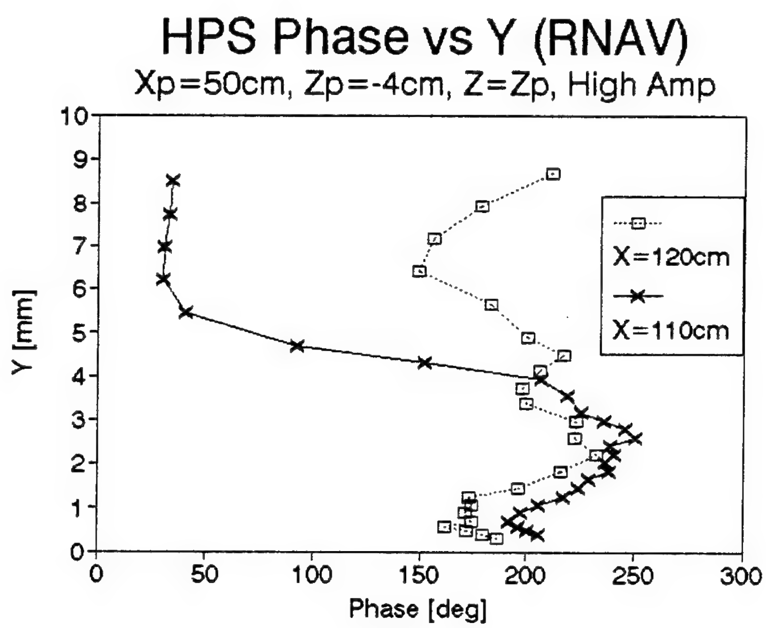
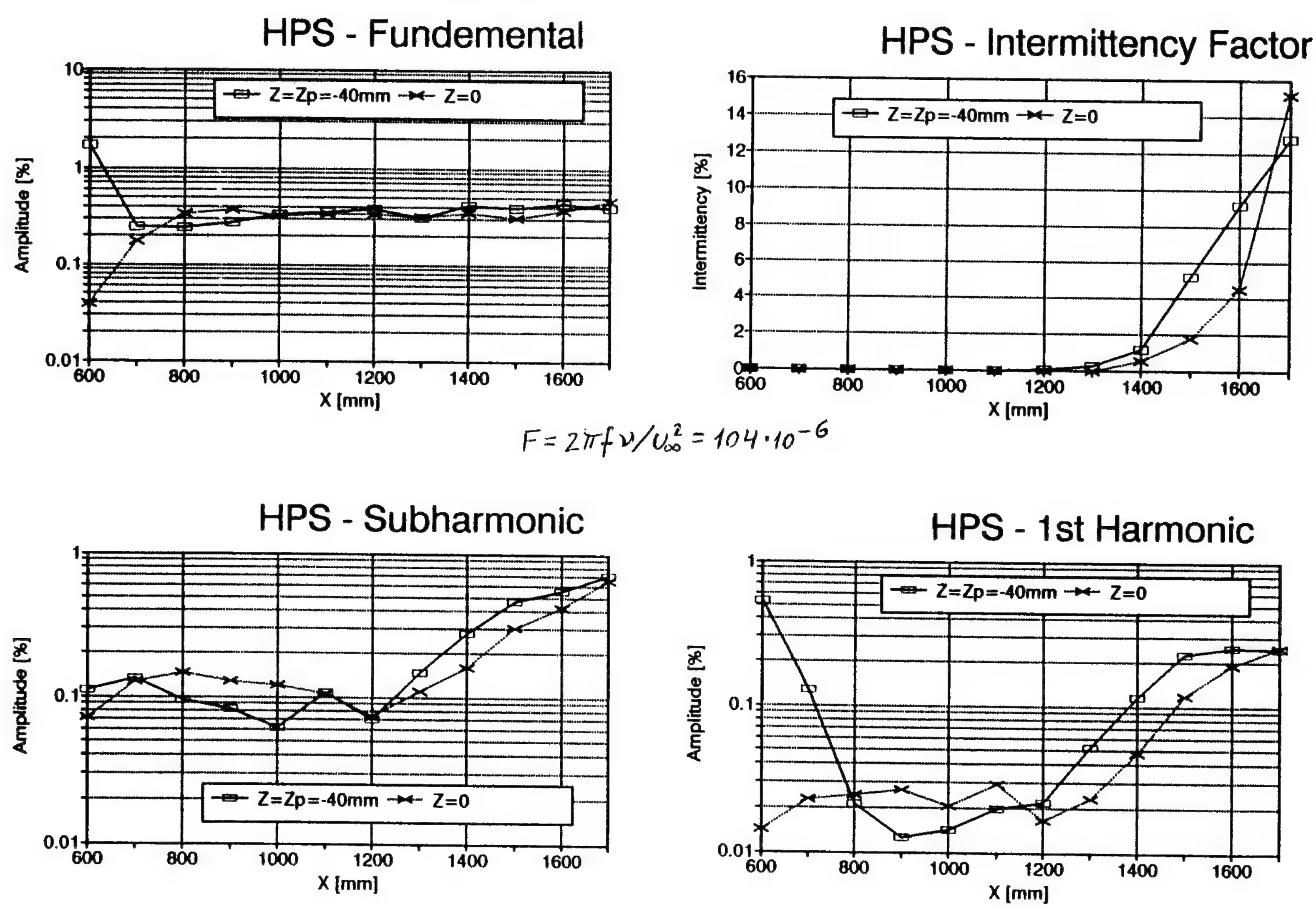

HPS Phase vs Y (RNAV)
Xp=50cm, Zp=-4cm, Z=Zp, High Amp
X=120cm
X=110cm
Y [mm]
Phase [deg]
0
1
2
3
4
5
6
7
8
9
10
50
100
150
200
250
300

Fig. 2



$F = 2\pi f \nu / U_\infty^2 = 104 \cdot 10^{-6}$

Fig. 3

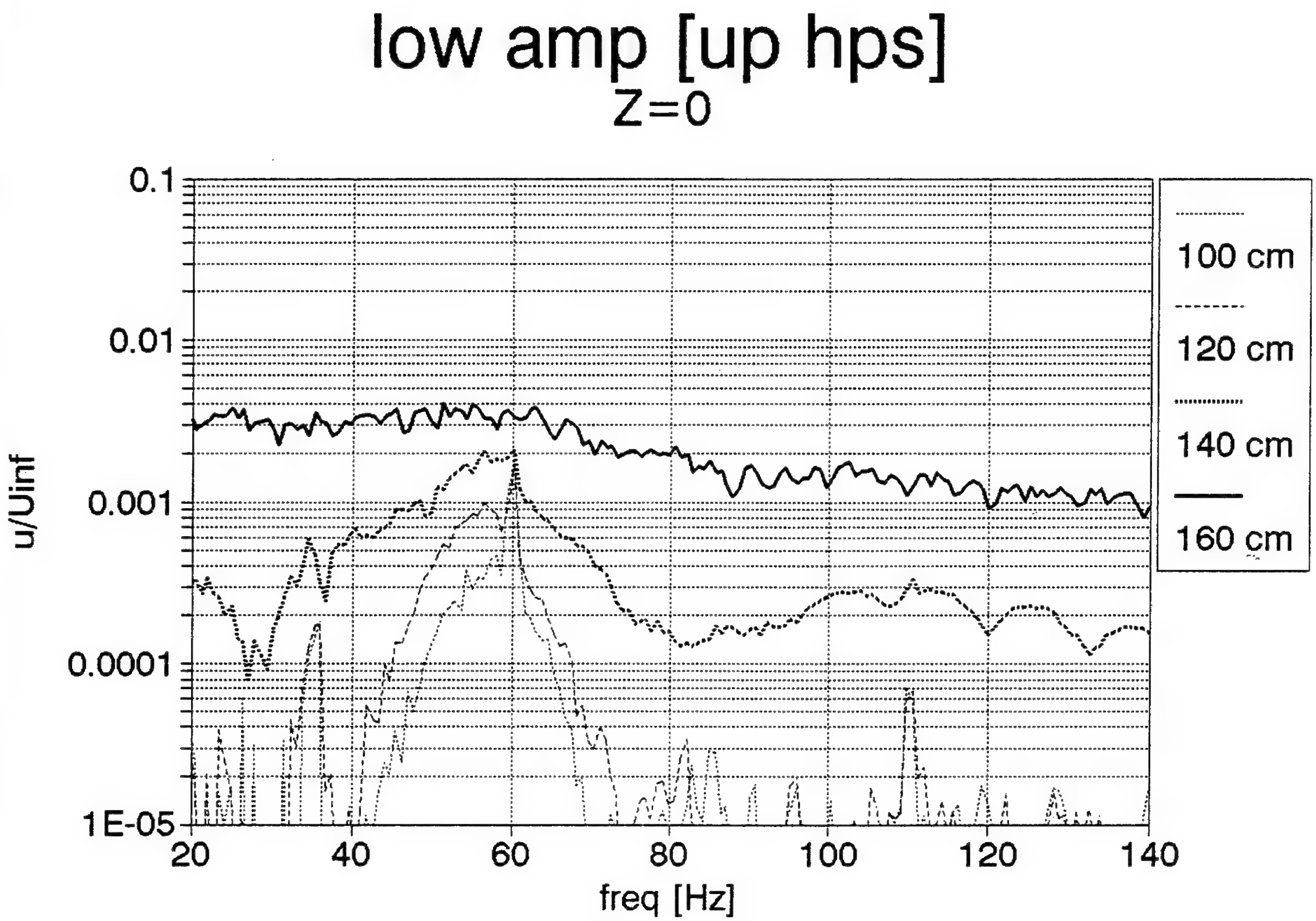
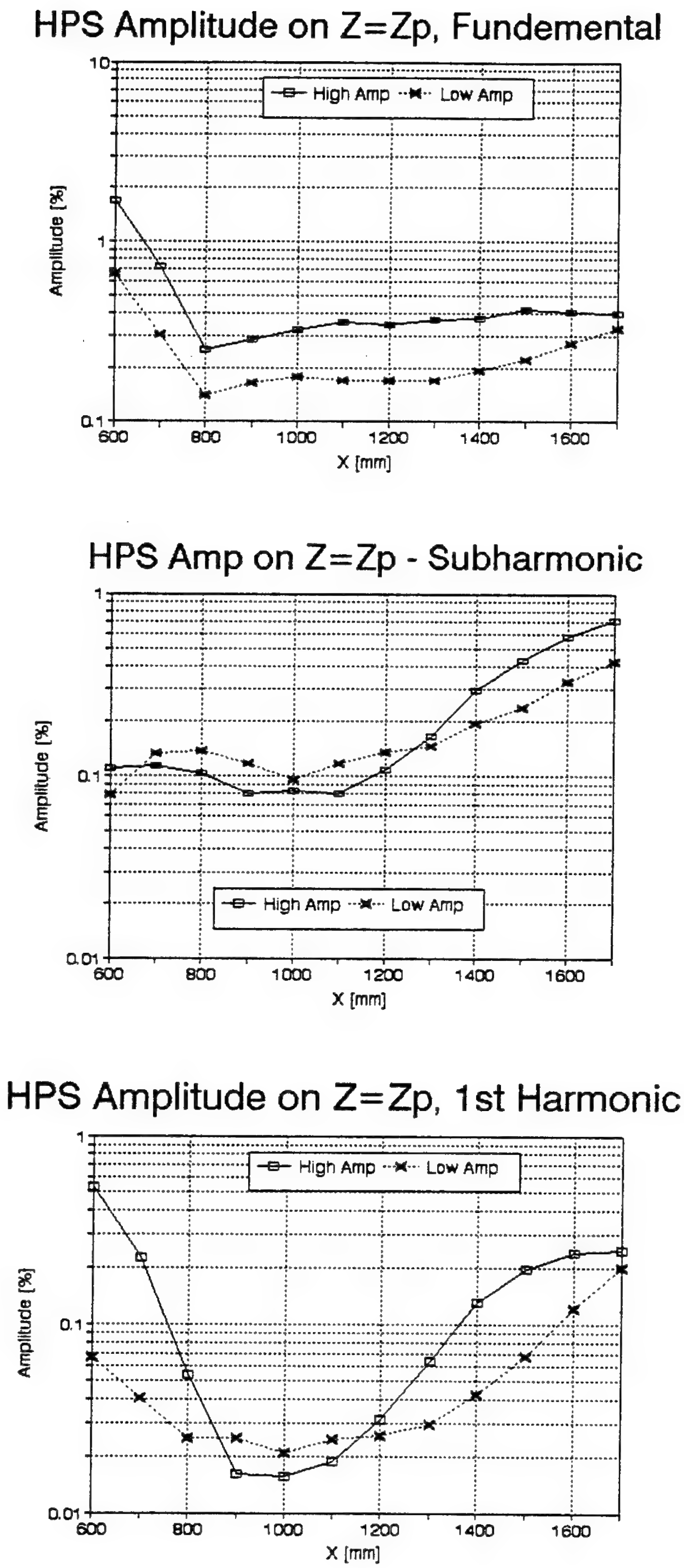

low amp [up hps]
Z=0
0.1
0.01
0.001
0.0001
1 E-05
u/Uinf
20
40
60
80
100
120
140
freq [Hz]
100 cm
120 cm
140 cm
160 cm

Fig. 4


HPS Amplitude on Z=Zp, Fundemental
High Amp
Low Amp
Amplitude [%]
X [mm]
10
1
0.1
600
800
1000
1200
1400
1600
HPS Amp on Z=Zp - Subharmonic
High Amp
Low Amp
Amplitude [%]
X [mm]
1
0.1
0.01
600
800
1000
1200
1400
1600
HPS Amplitude on Z=Zp, 1st Harmonic
High Amp
Low Amp
Amplitude [%]
X [mm]
1
0.1
0.01
600
800
1000
1200
1400
1600

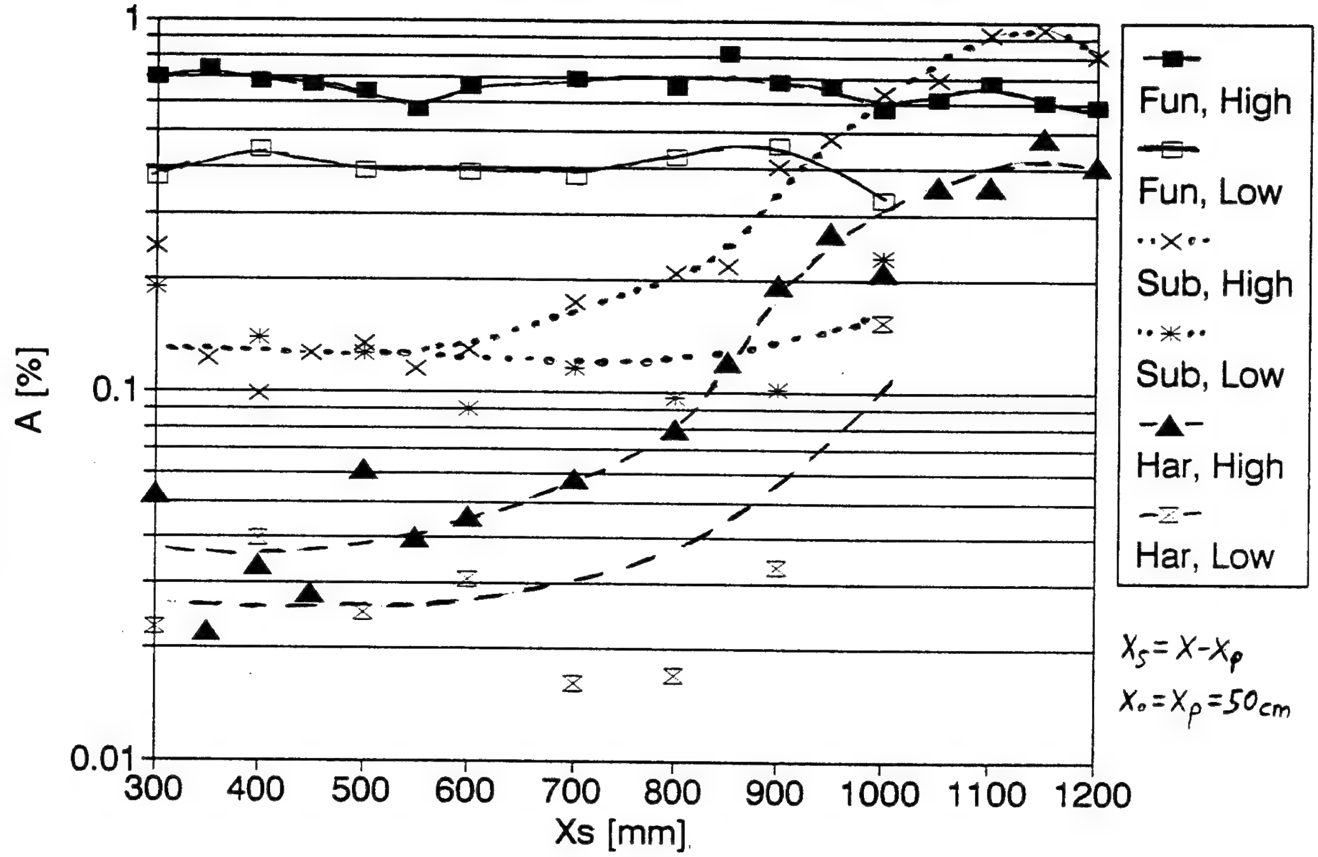
(a)

(b)

(c)

Fig. 5

THPS Amp on Z=0 vs X



THPS Interm. factor on Z=0 vs X

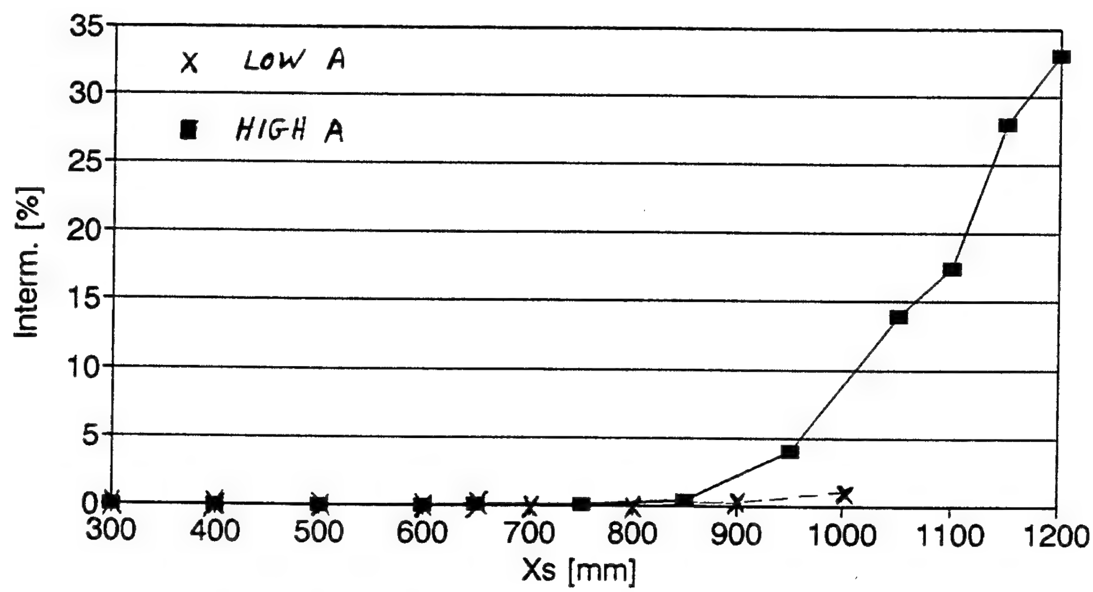


Fig. 6

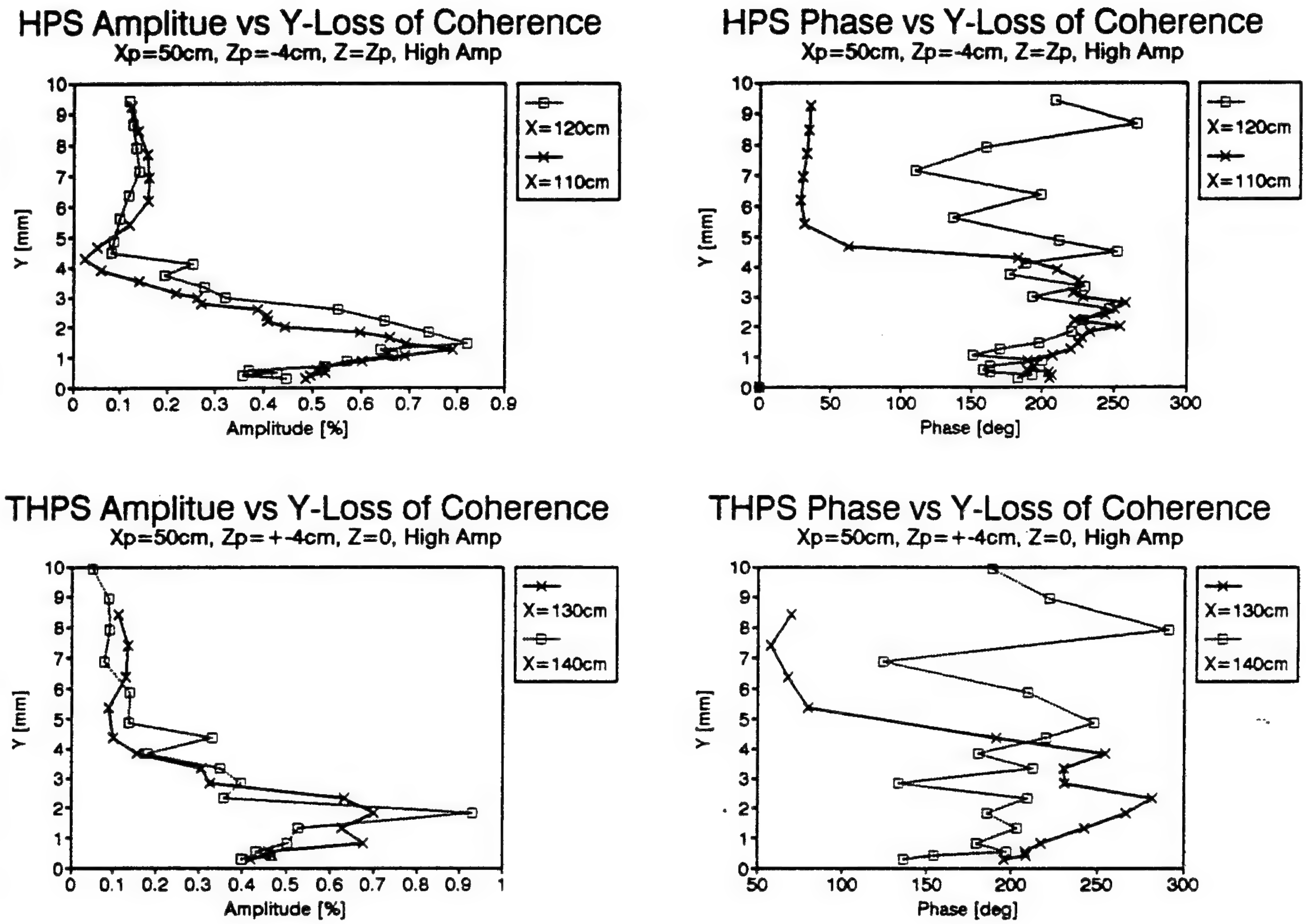

HPS Amplitue vs Y-Loss of Coherence
Xp=50cm, Zp=-4cm, Z=Zp, High Amp
Y [mm]
Amplitude [%]
X=120cm
X=110cm
HPS Phase vs Y-Loss of Coherence
Xp=50cm, Zp=-4cm, Z=Zp, High Amp
Y [mm]
Phase [deg]
X=120cm
X=110cm
THPS Amplitue vs Y-Loss of Coherence
Xp=50cm, Zp=+-4cm, Z=0, High Amp
Y [mm]
Amplitude [%]
X=130cm
X=140cm
THPS Phase vs Y-Loss of Coherence
Xp=50cm, Zp=+-4cm, Z=0, High Amp
Y [mm]
Phase [deg]
X=130cm
X=140cm

Fig. 7.

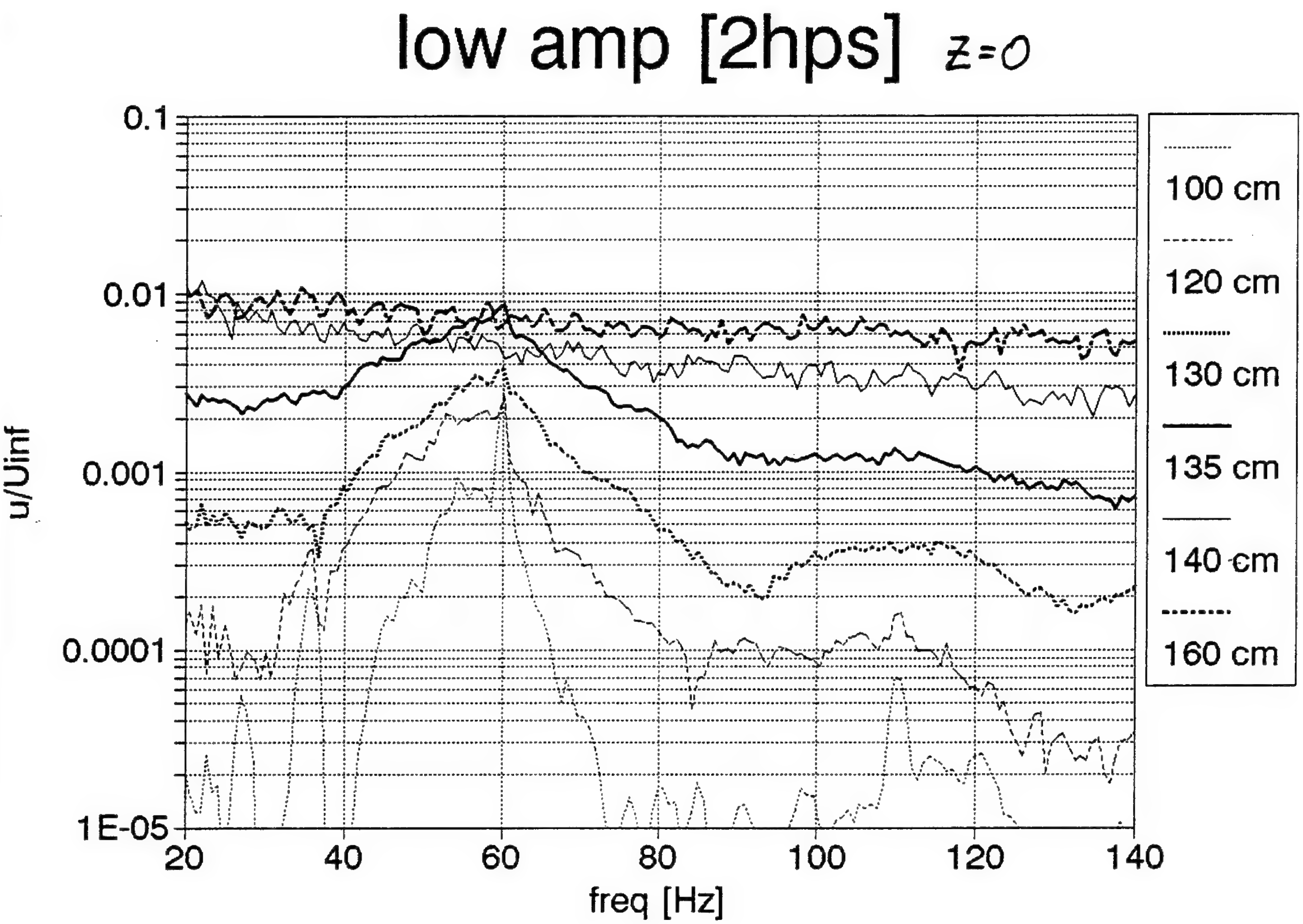

low amp [2hps] z=0
0.1
0.01
0.001
0.0001
1 E-05
u/Uinf
20
40
60
80
100
120
140
freq [Hz]
100 cm
120 cm
130 cm
135 cm
140 cm
160 cm

Fig. 8

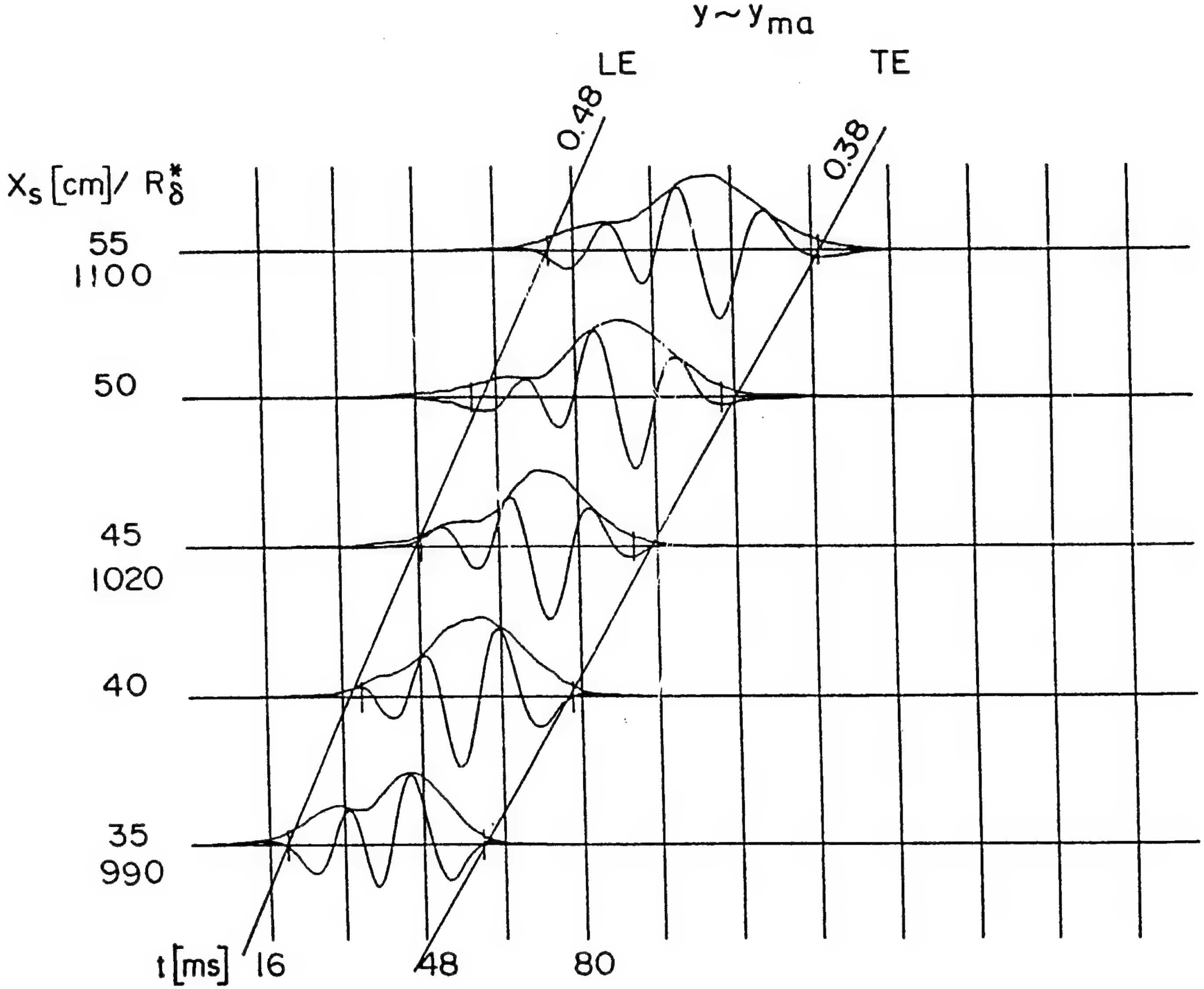


Fig. 9 Velocity change due to WP passage and envelope shape at $R_{\delta}{*}$=990 to 1100 (X_s=35 to 55cm, 5cm intervals), $Y=Y_{ma}$.

TWP Interaction. X=200cm Z=2cm Yma

Xp=30cm Zp=-4 and 8 cm Uinf=9.0

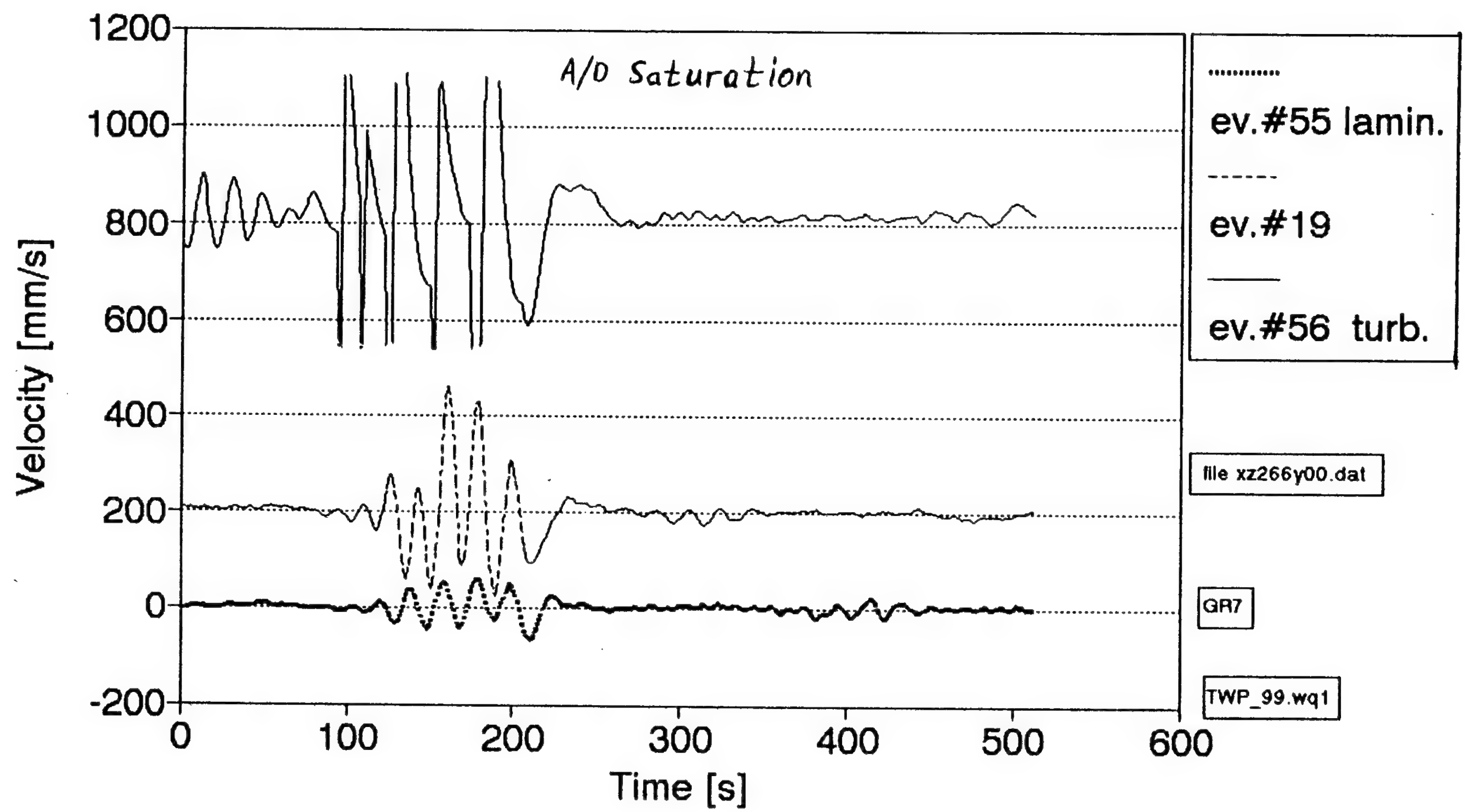


Fig. 10

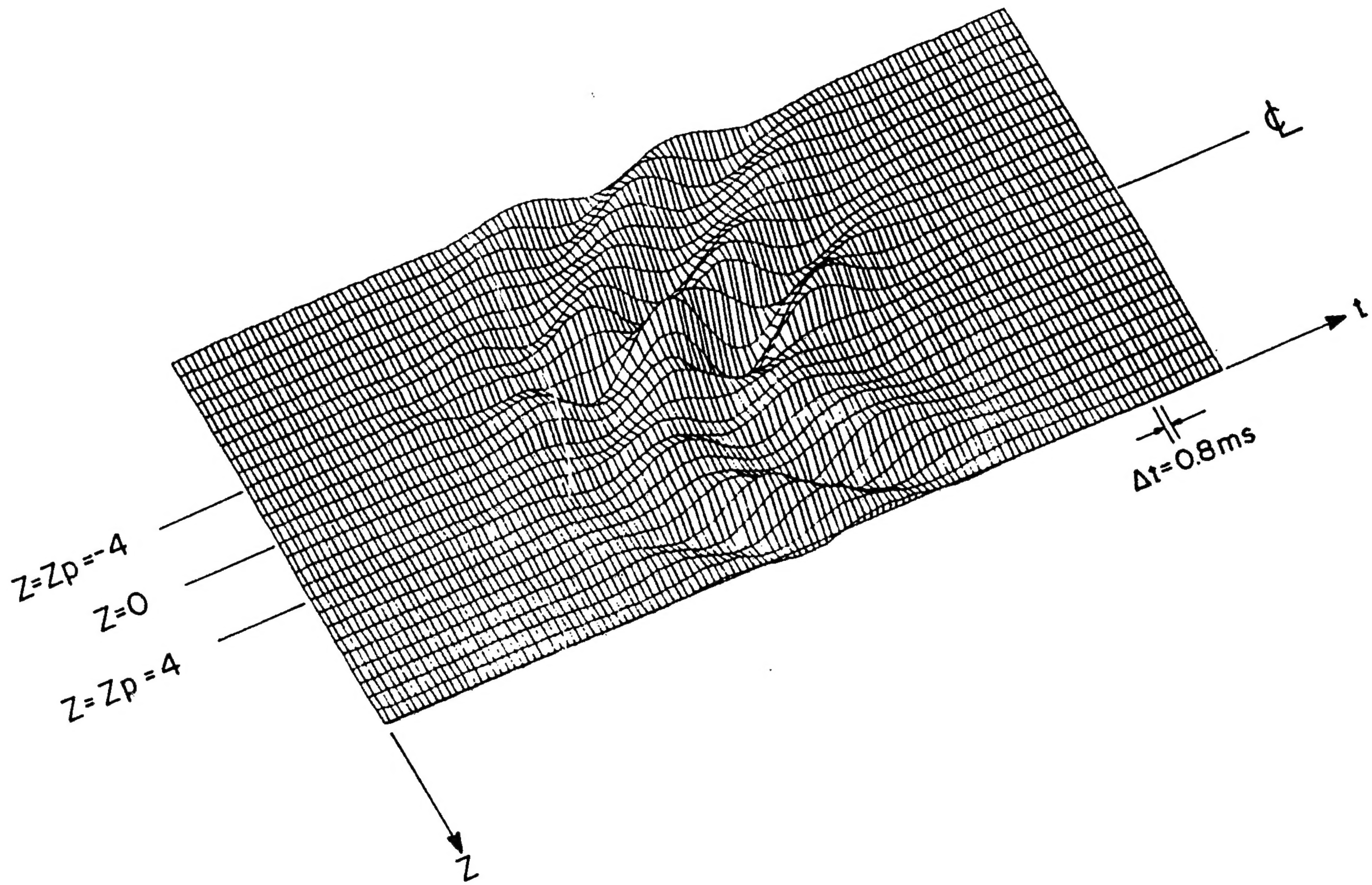


Fig. 11 The velocity change due to the TWP passage at $R_{\delta^*}=1100$ ($X_s=55cm$), $Y \simeq Y_{ma}$, the whole TWP span.

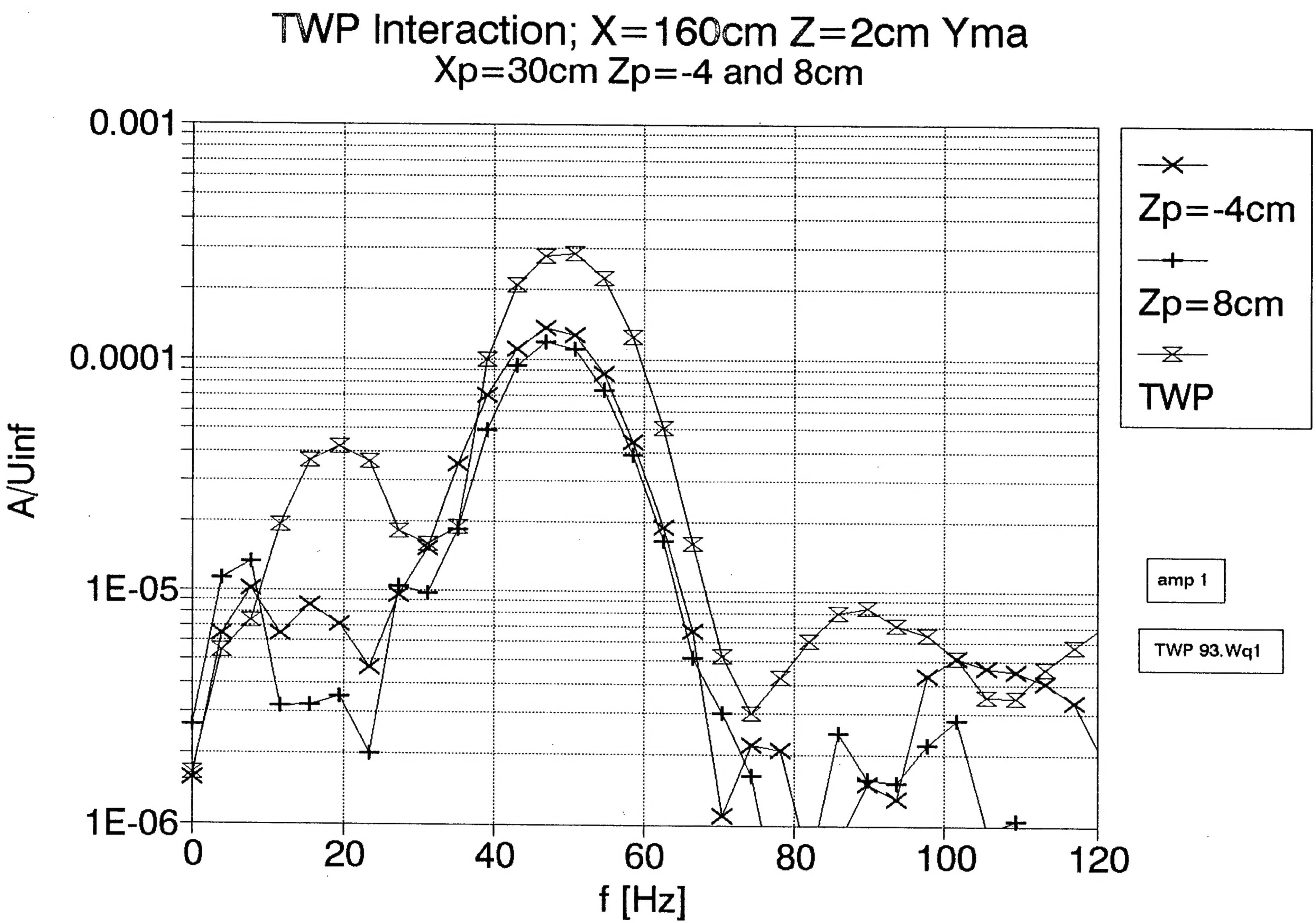
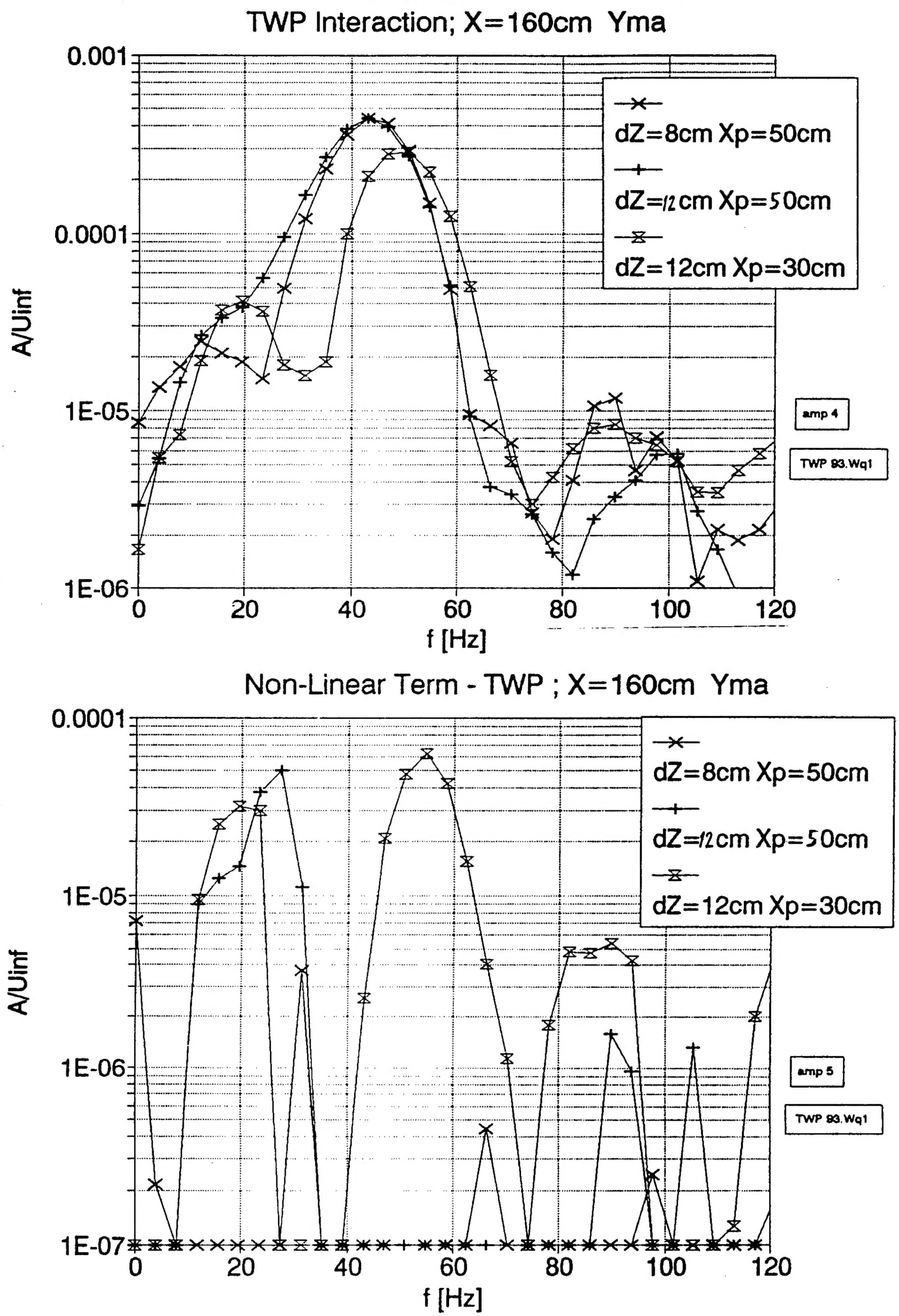

TWP Interaction; X=160cm Z=2cm Yma
Xp=30cm Zp=-4 and 8cm
0.001
0.0001
1E-05
1E-06
A/Uinf
0
20
40
60
80
100
120
f [Hz]
Zp=-4cm
Zp=8cm
TWP
amp 1
TWP 93.Wq1

Fig. 12



TWP Interaction; X=160cm Ymax
0.001
0.0001
1E-05
1E-06
A/Uinf
0
20
40
60
80
100
120
f [Hz]
dZ=8cm Xp=50cm
dZ=12cm Xp=50cm
dZ=12cm Xp=30cm
amp 4
TWP 93.Wq1
Non-Linear Term - TWP ; X=160cm Yma
0.0001
1E-05
1E-06
1E-07
A/Uinf
0
20
40
60
80
100
120
f [Hz]
dZ=8cm Xp=50cm
dZ=12cm Xp=50cm
dZ=12cm Xp=30cm
amp 5
TWP 93.Wq1

Fig. 13

TWP Interaction; X=200cm Z=2cm Yma

Xp=30cm Zp=-4 and 8cm

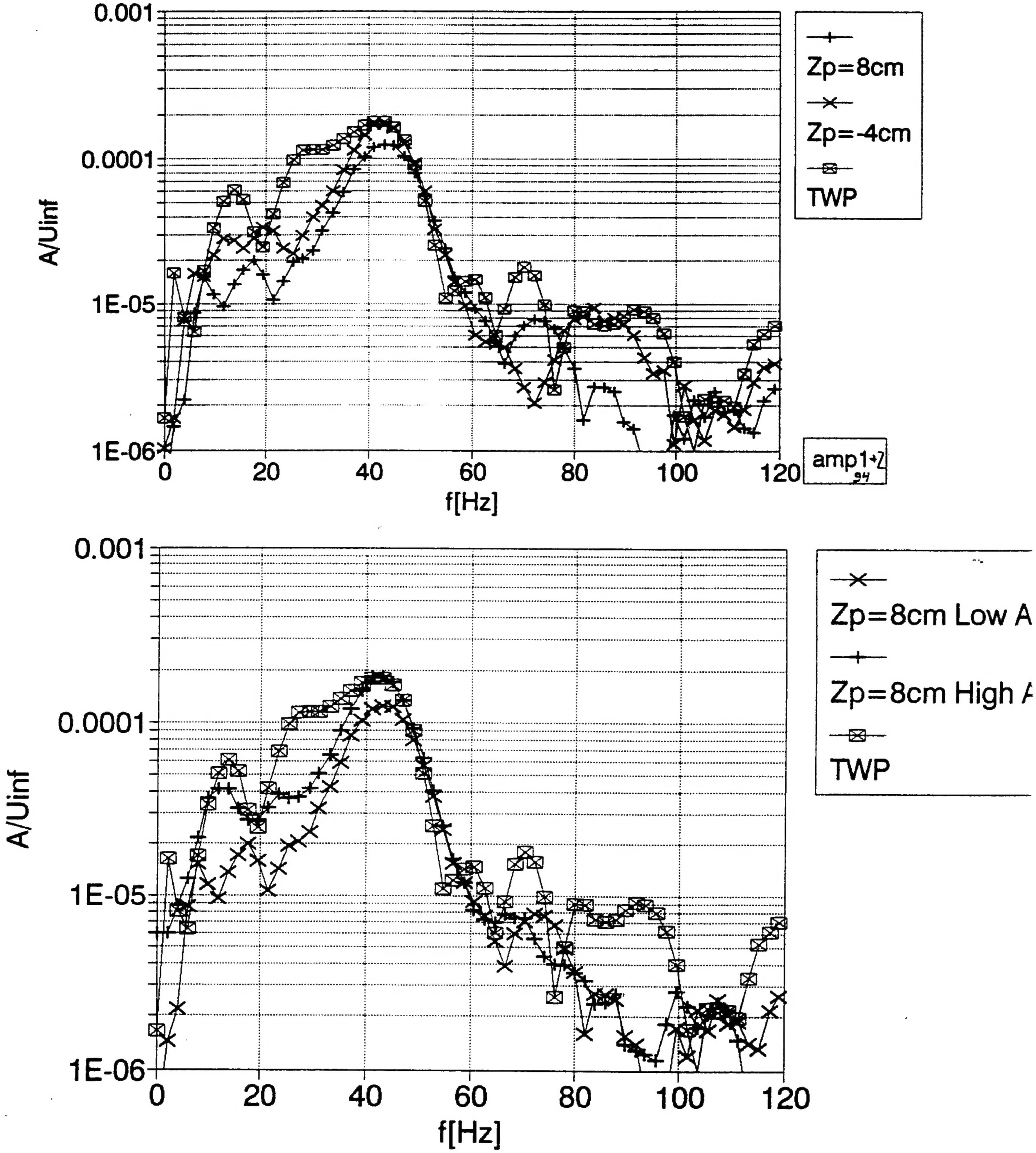


Fig. 14